Variability of plyometric and ballistic exercise technique maintains jump performance

ABSTRACT

The aim of this study was to investigate changes in vertical jump technique over the course of a training session. Twelve plyometric and ballistic exercise trained male athletes (age = 23.4 ± 4.6 years, body mass = 78.7 ± 18.8 kg, height = 177.1 ± 9.0 cm) performed three sets of 10 repetitions of drop (DJ), rebound (RJ) and squat jumps (SJ). Each exercise was analysed from touch down to peak joint flexion and peak joint flexion to take-off. SJ where analysed from peak joint flexion to take-off only. Jump height, flexion and extension time and range of motion, and instantaneous angles of the ankle, knee and hip joints were measured. Separate one-way repeated ANOVAs compared vertical jump technique across exercise sets and repetitions. Exercise set analysis found SJ had lower results than DJ and RJ for the angle at peak joint flexion for the hip, knee and ankle joints and take-off angle of the hip joint. Exercise repetition analysis found the ankle joint had variable differences for the angle at take-off, flexion and extension time for RJ. The knee joint had variable differences for flexion time for DJ and angle at take-off and touch down for RJ. There was no difference in jump height. Variation in measured parameters across repetitions highlights variable technique across plyometric and ballistic exercises. This did not affect jump performance, but likely maintained jump performance by overcoming constrains (e.g. level of rate coding).

INTRODUCTION

Plyometric and ballistic exercises are common place in athletic training for many sports to improve vertical jump performance. Plyometric exercise refers to the use of the stretch-shortening cycle, where a high-intensity eccentric contraction occurs immediately before a rapid concentric contraction (18). Plyometric exercises usually involve various types of body weight jumping, such as drop jumps (DJ) and countermovement jumps (CMJ). Ballistic exercise is defined by the explosive release of the body in to the air, but the overall duration of the exercise is longer mainly due to an extended ground contact time, such as a squat jump (SJ).

Numerous studies have found improvement in vertical jump performance after a period of vertical jump training incorporating both ballistic and plyometric exercises. A meaningful improvement of 4.8 cm have been found in CMJ height after six weeks of vertical jump training in basketball athletes (19). Further significant improvements of 13.2% have been found in CMJ height after six weeks of additional vertical jump exercise in athletic training (24). Periods of plyometric training have also been found to increase vertical jump height in both male (7) and female athletes (22), thus justifying its inclusion in athletic training to improve jump performance in all athletic populations.

Plyometric and ballistic exercise technique has been extensively researched to find methods of improving jump performance (8, 20, 25, 26). Jump height is considered the main performance output of a ballistic and plyometric exercise, therefore is extensively measured my strength and conditioning coaches to identify the best jump technique. A Greater squat depth is argued to produce a greater jump height in a SJ (8, 20). A greater net impulse was found with greater squat depth (8), due to greater amount of time taken to execute the jump, which may cause the greater jump height. Although, a CMJ has found to have a greater jumper height than a SJ, and further had a greater impulse during smaller squat depths (20). Thus, opposite of SJ, a greater force is produced relative to time in a CMJ with less of a squat depth creating a greater jump height.

The literature suggests several methods for increases in jump height caused by better jump technique, therefore jump height alone does not identify how said jump is achieved. Measurement of kinetic parameters, such as peak ground reaction force or impulse, would better identify vertical jump intensity, but would be influenced by range of motion and jump timings during different phases (i.e. touchdown, peak joint flexion and take-off) of a ballistic or plyometric jump. Knee and ankle flexion have found to increase after a CMJ fatigue protocol by 7.0^{o} and 10.6^{o}, while vertical ground reaction force did not significantly differ (26). This highlights a change in jump technique to maintain vertical ground reaction force, therefore optimal jump technique is influenced by kinematic measures. Therefore, if the strength and conditioning coach monitored kinematic parameters, such as range of motion and jump timings, it would provide insight into if and/or how the range of motion and timing of said range of motion influence jump technique to achieve jump height (i.e. if a shallower but faster range of movement is achieved then forces will likely be larger compared to a deeper but slower range of movement and if this impacts of jump height).

Research agrees jump technique between each type of plyometric and ballistic exercise differs, however, all research has looked at plyometric and ballistic exercise in isolation, where the strength and conditioning coach will employ them in a training session. Therefore, it is not known if the jump technique will differ between plyometric and ballistic exercise in a training session or between repetitions in the same exercise set. It is important for the strength and conditioning coach as they will be able to identify the best jump technique to bring about greater jump performances. Therefore, the aim of this study was to investigate kinematic changes of plyometric and ballistic exercise technique over the course of a training session to identify the best jump technique. It is hypothesized that as drop jump exercise produces the greatest jump height, will have to best jump technique. Furthermore, jump height between exercise repetitions will decrease throughout the exercise set, therefore the best jump technique will be at the start of the exercise set.

METHOD

Experimental approach to the Problem

Data for this study was collected from 12 athletes, experienced in plyometric and ballistic exercise training. Prior to completing the study, all participants passed the NSCA recommendations for prerequisites of completing plyometric exercise (2). This study was a cross sectional study design.

Subjects

Twelve male athletes (age = 23.4 ± 4.6, body mass = 78.7 ± 18.8 kg, height = 177.1 ± 9.0 cm), experienced in plyometric and ballistic exercise training and participated in lower body power sports (e.g. Judo, Javelin, Sprinting), volunteered to participate in the study. All participants competed at club level, and testing was complete in the off-season of each sport.

The study was approved by a University ethics board prior to starting. All participants received a clear explanation of the study including the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. No funding or endorsements were used in this study

Procedures

All participants completed a familiarisation and a testing session separated by 72 hours. All sessions were complete at the same time of day to allow for variations in strength gains due to training at different times of the day (23). Participants were asked to refrain from any form of exercise 72 hours before testing. Participants were further asked to maintain the same level of hydration and continue a regular eating pattern prior to each laboratory visit.

Familiarisation and testing sessions were identical except no measurements were taken during the familiarisation session. All sessions involved the same plyometric exercises; DJ, rebound jump (RJ) and SJ. The DJ involved participants dropping off a 40 cm high box leading with their dominant leg. Dominant leg was determined by asking the participant. The 40 cm drop height was selected as it is reportedly in the range of optimal dropping height (40-60 cm), measured in 19 young participants (1). The RJ involved repetitive CMJ to a self-selected depth, initiated by a CMJ. The first jump was not analysed due to it not been a true rebound jump, as a jump did not precede it. The SJ involved a countermovement to a self-selected depth to initiate the beginning of the jump, but participants were instructed to hold for three seconds at the bottom of the countermovement before completing a maximal jump. If the position was not held at the bottom of the countermovement for three seconds, the jump was discounted and completed again.

During the DJ and RJ all participants were instructed to jump as high and as fast as possible with minimum ground contact, whereas for the SJ participants were instructed to jump as high as possible. All jumps were completed with arm swing to reflect a true training session and achieve maximal height.

All sessions started with a warm up, consisting of 10 minutes cycling at 100 W, followed by 10 minutes of dynamic stretches. The participants then completed three submaximal repetitions of each plyometric and ballistic exercise with two minutes rest in between. This allowed for the experimenter, an accredited strength and conditioning coach, to assess appropriate technique. Appropriate technique for all exercises included bilateral landing, with stable ankle, knee and hip joints, with no forward trunk lean.

The familiarisation and testing session consisted of three sets of 10 repetitions of DJ, RJ and SJ, completed in that order to represent a typical training session. Three minutes of rest between sets was allowed to meet recommendations of an optimal work to rest ratio of 1:5 to 1:10 (2). The number of foot contacts, 120, matched recommendations for intermediate athletes as all athletes had experience of plyometric and ballistic exercises in their own training and sport (2).

All exercises were completed on a force plate (Bertec, Columbus, U.S.A). The force plate was used to determine parameters mentioned later in this methodology. 10 mm spherical markers were attached to the fifth metatarsal, lateral malleoli, knee, greater trochanter and shoulder on the dominant side of all participants. Placement of markers has been used in previous research (12). The markers were tracked using a 6-camera three-dimensional (3D) motion capture system (Proreflex, Qualisys, Savadalen, Sweden) to identify bony landmarks.

Motion analysis software (Qualisys track manager, Qualisys, Savadalen, Sweden) was used to measure ankle, knee and hip angles at touch down, peak joint flexion and take-off for DJ and RJ. Touch down was determined by the point when the right foot first touched the ground, shown by a force greater than 20 N on the force plate. Peak joint flexion was determined by maximum knee flexion, while take-off was determined by the last contact of the right foot on the ground, shown by a force less than 20 N on the force plate.

Ankle, knee and hip angles at first movement, peak joint flexion and take-off were measured for the SJ. First movement was determined by an increase in force by 20 N on the force plate. Peak joint flexion and take-off for SJ were determined in the same manner for DJ and RJ.

Flexion and extension range were calculated for DJ and RJ from the difference between angle at touch down and peak joint flexion, and the difference between angle at the peak joint flexion and take-off, respectively. Flexion and extension time for DJ and RJ were determined by the time difference of the same movements mentioned for flexion and extension range. Flexion and extension range were calculated for SJ from the difference between angle at first movement and peak joint flexion, and the difference between angle at the peak joint flexion and take-off, respectively. Flexion and extension time for SJ were determined by time difference for the same movements mentioned for flexion and extension range. Jump height was measured by the greatest displacement of the greater trochanter reflective marker relative to take-off.

Statistical analyses

Statistical analysis was completed on sets of plyometric and ballistic exercises (exercise sets) and repetitions of plyometric and ballistic exercises (exercise repetitions) to determine differences between vertical jump exercise sets and repetitions. Exercise sets were calculated by the mean scores for each vertical jump exercise set. Exercise repetitions were calculated by the mean of each repetition of vertical jump exercise.

Initial testing of normality and homogeneity of variance of data was completed to determine the use of a parametric or none parametric tests. For data that passed these tests, separate one-way repeated ANOVA tests were complete to determine differences between vertical jump exercise sets and exercise repetitions. Where significant differences were detected a paired samples t-test was used to determine the differences.

If the test of normality or homogeneity of variance was not met, a non-parametric equivalent test was complete. In this case, the Freidman's test determined any differences between vertical jump exercise sets and exercise repetitions. Where significance was found, a Wilcoxon's signed rank test was completed with manual Bonferroni adjustments to determine the differences. Significance for all tests was set at $p < .05$.

Cohen's *d* effect size (ES) was used to calculate practically meaningful differences among all measured parameters. ESs of <0.2, 0.2-0.6, 0.61-1.2 and >1.2 were considered trivial, small, moderate and large, respectively (3). Infraclass correlations coefficients (ICC) were calculated of each exercise for each kinematic parameter to determine reliability of each kinematic measurement. The ICC classifications of Fleiss (less than 0.4 was poor, between 0.4 and 0.75 was fair to good, and greater than 0.75 is excellent) were used to describe the range of ICC values (10). All statistical analyses were performed in SPSS (version 22.0, SPSS Science Inc, Chicago, IL, USA).

RESULTS

ICC results show kinematic measures of plyometric and ballistics exercises to be reliable (Table 1). Results of exercise sets analysis showed significant differences between all kinematic parameters. Post hoc analysis of exercise set results are shown in Tables 2, 3 and 4.

Insert table 1 about here

Insert table 2 about here

Insert table 3 about here

Insert table 4 about here

Results of the analysis of exercise repetitions for the knee joint showed significant differences between repetitions for DJ flexion time (P = 0.01, ES = 0.84 – 0.58). The repetition significant difference for DJ knee flexion time is shown in Figure 1. RJ knee joint angle at touch down (P = 0.03, ES = 1.10 - 0.66), angle at take-off (P = 0.03, ES = 0.78 – 0.58) and flexion time (P = 0.04, ES = 0.72 – 0.84) found significant difference between repetitions. The repetition significant differences for the knee joint of the RJ are shown in Figure 2. SJ angle at touch down (P = 0.01, ES = 0.78 – 0.55) and extension range (P = 0.01, ES = 0.84 – 0.55) found significant differences between repetitions for the knee. The significant repetition differences of the knee joint for the SJ are shown in Figure 3. Significant differences of the ankle joint between repetitions were found for DJ angle at touch down (P = 0.03, ES = 0.89 – 0.72), with significant differences shown in Figure 4. RJ ankle angle at take-off (P = 0.03, ES = 0.81 – 0.66), flexion time (P = 0.01, ES = 0.81 – 0.58) and extension time (P = 0.05, ES = 0.81 – 0.58) found significant difference between repetitions. The significant differences between repetitions are shown in Figure 5. Significant differences of the hip joint between repetitions were only found for SJ angle at touch down (P = 0.01, ES = 0.89 – 0.58). The significant difference between repetitions are shown in Figure 6.

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DISCUSSION

This is the first study to investigate plyometric and ballistic exercise technique via kinematic measures over the course of a training session to identify optimal jump technique. This study found kinematic measures of vertical jump exercises to be reliable, with all kinematic parameters being classed as excellent except for touch down, flexion range and extension time for SJ being classed as fair to good. This agrees with Malfait et al. (2014) finding a 3.2^0 to 3.5^0 variability in lower limb joint angles between a series of DJ, leading to the authors reporting DJ kinematic data to be reliable (17). Ford et al. (2007) is in further agreement finding ICCs ranging from 0.933 to 0.993 for lower limb joint angles measured during drop jumps (11). These studies support the present study's findings of kinematic data being a reliable measure of plyometric and ballistic jump technique, therefore it can be suggested that each kinematic variables are consistent and accurate and may be used to measure optimal vertical jump technique.

Analysis of exercise sets found SJ to be significantly different from DJ and RJ for several kinematic variables across all joints. Similar results have been reported in previous research, finding differences between flexion angles and angles at take-off for the hip, knee and ankle joints between CMJ and SJ (16). This highlights that there are different techniques utilized between vertical jump exercises. Therefore, the strength and conditioning coach should be aware of different techniques as this may influence the technical aspect of training a vertical jump exercise.

The present study found DJ jump height to be lower than RJ and SJ. This is not consistent with previous literature with numerous studies finding DJ and RJ to have a greater jump height than SJ. Previous research found a 23 cm difference between DJ and SJ (12), and an average of 2.4 cm difference between CMJ and SJ (4). This was attributed to agonist muscles having greater time to develop more cross-bridge attachments during muscle contraction. This led to greater moments at the hip, knee and plantarflexion leading to greater force production (4). Greater electromyography activity in active muscles during a CMJ has been found, which was attributed to greater muscle activation and elastic recoil (9). Further suggested mechanisms involve a pre-stretch created by the countermovement in DJ and RJ led to storage of energy in the serial elastic elements, which was later utilized when muscles act concentrically to increase jump height (13). The literature suggests numerous reasons for the greater jump height in DJ and RJ. It would be reasonable to suggest that not one mechanism is the cause of the greater jump height, but a combination of all mechanisms.

Although, Kotzamanidis et al. (2005) is in agreement with the present study finding DJ to have the lowest jump height of 20.07 cm, compared to SJ and RJ with jump heights of 25.51 cm and 27.83 cm, respectively (14). This may be due to a longer pre-stretch time leading to less energy transferred to the series elastic element, causing a lower net impulse, for further utilization. Participants not been able to attenuate the large impact forces on initial landing may cause the longer pre-stretch time where less force is transferred to the propulsive phase of the jump. Therefore, use of a lower drop height for DJ may benefit some athletes that cannot attenuate impact forces from larger drop heights. Ground reaction forces can be used to monitor attenuation of impact forces to help the strength and conditioning coach progress drop heights for DJ exercises.

Results of exercise repetition analysis show variability between kinematic parameters. For example, during the RJ exercise, the knee angle at touch down for repetition 10 of set 1 is significantly different to repetition 4, 7 and

9 of the same set, but repetition 10 of set two has no significant difference to any other repetitions. This highlights variation in vertical jump technique throughout the course of the training session. Similar variability was found when investigating basketball free throw technique (5). The authors found variability in wrist and elbow angle to adapt to constraints in release parameters of the ball (5). The variability of technique were made to maintain shooting accuracy, therefore shooting technique changed to maintain performance.

Davids et al. explained constraints to be boundaries that interact to limit the optimal movement state (6). Constraints are characterised in to three groups. Individual where constraints are located inside the body. External when constraints are in the environment and task where constraints are related to a skill or specific task (6). Latash et al. argued that the body will adapt its output to compensate for the constraints imposed upon it, so that movement is maintained as close to optimal as possible (15). Therefore, in the present study, the jump technique variability is likely reflective of the body compensating for the constraints experienced. As no significant difference was found between vertical jump exercise repetitions and jump height, it is argued that the jump technique variability maintains jump performance.

The amount of technique variation differed between vertical jump exercises as DJ only experienced variation at the knee joint, while RJ and SJ elicited variation at the hip, knee and ankle joints. This may be due to the level of experience of a task. Comparison of expert and novice marksmen during a pistol target shooting task found experts to have different angles at the shoulder and elbow but not the wrist during target shooting (21). However, novices had variability at the wrist joints only (21). The authors suggested the experts were able to employ a flexible degrees of freedom, (21). Degrees of freedom are the numerous independent ways an athlete can move (6), therefore, experts employed a different degree of freedom to each individual target shot depending on the constraints imposed upon them. The novices could not and used a more rigid degrees of freedom approach. This phenomenon is known as functional variability allowing experts to use variable technique to maintain performance (6). In the present study, participants were able to employ a functional variability approach for the RJ and SJ, but not the DJ. The rigid technique during DJ may be due to participants not been able to attenuate impact forces upon landing, therefore the drop height may have been too high.

It may be beneficial for strength and conditioning coaches to expose a range of constrains on vertical jump exercises allowing athletes to gain a wider experience of constraints. This would broaden the athletes experience of constraints allowing a greater functional variability, so jump performance can be better maintained.

Even though technique variability aids jump performance maintenance it is not known the affect this has on kinetic parameters of the jump. The kinetic parameters are important as they explain the force production that drives movement. Weinhandle et al. investigated the kinetics and kinematics of a DJ under fatigued and none fatigued states (26). Ankle, knee and hip angles at 100 ms after touch down were found to significantly differ between an unfatigued and fatigued state, therefore supporting kinematics to vary between jump repetitions. However, force production during this period did not differ (26), suggesting force production does not change between repetitions of CMJ and therefore kinetic parameters do not vary between repetitions. However, this study only analyses one small period of one type of vertical jump. It is not known if kinematic technique affects kinetic technique during any other period of a DJ, or other types of vertical jumps. Further research is needed to determine this.

PRACTICAL APPLICATION

Variation in vertical jump technique is employed to overcome constraints imposed on the athlete, allowing the athlete to maintain jump performance. Therefore, there is no optimal jump technique for plyometric and ballistic exercises. It may be beneficial for the strength and conditioning coach to train variation during vertical jump exercise. This can be achieved by exposing a range of constrains on vertical jump exercises allowing athletes to gain a wider experience of constraints that may affect them in competition. Incorporation of a range of vertical jump exercises in training would also allow athletes to learn and utilise functional variability, so adaptation to constraints is easier.

A more rigid vertical jump technique was used for the DJ, as there were fewer differences in kinematic measures. This was due to participants not been able to attenuate impact forces upon landing, suggesting drop height was too high. This highlights to the S&C coach that the athlete is not strong enough, and thus needs to develop strength. Therefore, this is a method an S&C coach can use to identify if their athletes are strong enough to attenuate landing force that may be experience in their sport.

Vertical jump kinematics differ between plyometric and ballistic exercise, thus there are different jump technique of each exercise. The strength and conditioning coach should be aware of this as it may affect the method of training the technical aspect of a vertical jump.

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Table 1: Interclass correlation coefficient results

	Drop Jump	Rebound Jump	Squat Jump
First ground contact	0.975	0.980	0.932
Greatest jump depth	0.962	0.974	0.656
Toe off	0.933	0.963	0.943
Flexion range	0.986	0.927	0.693
Extension range	0.979	0.799	0.961
Flexion time	0.984	0.924	0.974
Extension time	0.972	0.983	0.736
Average angle velocity	0.885	0.923	0.926
Jump height	0.985	0.985	0.998

Table 2: Exercise set results of the knee joint.

	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 [c] (44.9 - 58.4)	49.3 [c] (40.2 - 54.5)	52.2 [a,b,c] (42.6 - 57.6)	62.5 [a,b,c] (52.9 - 67.9)	56.3 [a,b,c] (46.7 - 62.0)	60.7 [a,b,c] (51.2 - 66.3)
First Ground Contact (degrees)	147.0 (142.2 - 151.9)	146.6 (140.7 - 152.6)	146.2 (137.7 - 154.7)	147.1 (142.4 - 151.8)	147.2 (140.2 - 154.3)	147.9 (138.2 - 157.6)	152.1 (147.6 - 156.6)	151.1 (145.7 - 156.5)	151.2 (143.7 - 158.8)
Greatest Jump Depth (degrees)	108.0 (104.5 - 111.5)	107.6 (99.8 - 115.4)	106.8 (96.8 - 116.8)	107.8 (103.9 - 111.6)	107.4 (99.4 - 115.5)	106.5 [b,c] (96.2 - 116.7)	95.1 [a,b,c,d,e,f] (89.4 - 100.8)	102.7 (81.8 - 123.7)	96.9 [a,b,c] (86.4 - 107.3)
Toe Off (degrees)	156.0 (152.1 - 159.9)	155.0 (150.4 - 159.6)	156.1 (149.4 - 162.9)	158.5 (155.5 - 161.5)	157.8 (153.1 - 162.5)	157.1 (149.9 - 164.4)	157.1 (153.1 - 161.1)	156.6 (150.0 - 163.1)	157.5 (149.3 - 165.8)
Flexion Range (degrees)	39.0 (31.5 - 46.6)	40.0 (25.9 - 54.0)	39.3 (21.5 - 57.2)	42.1 (34.0 - 50.3)	39.5 (26.7 - 52.2)	42.2 (25.8 - 58.6)	57.2 [a,b,c,d,e,f] (50.6 - 63.8)	49.9 [a,g] (38.7 - 61.1)	53.0 [a,b,d] (42.7 - 63.2)
Extension Range (degrees)	48.0 (42.4 - 53.5)	47.6 (37.3 - 57.9)	49.4 (36.8 - 62.1)	53.5 (47.6 - 59.5)	49.3 (35.2 - 63.4)	52.2 (41.9 - 62.5)	62.5 [a,b,c,e,f] (55.6 - 69.4)	56.3 (42.9 - 69.7)	60.7 [a,b,c,g] (49.1 - 72.2)
Flexion Time (seconds)	0.13 (0.09 - 0.17)	0.12 (0.07 - 0.17)	0.13 (0.20 - 0.06)	0.19 (0.11 - 0.26)	0.16 (0.09 - 0.23)	0.17 (0.03 - 0.30)	1.42 [a,b,c,d,e,f] (1.04 - 1.81)	1.35 [a,b,c,d,e,f] (0.84 - 1.85)	1.48 [a,b,c,d,e,f] (0.47 - 2.50)
Extension Time (Seconds)	0.14 (0.11 - 0.17)	0.15 (0.10 - 0.21)	0.14 (0.07 - 0.22)	0.40 [a,b,c] (0.31 - 0.49)	0.39 [a,b,c] (0.26 - 0.52)	0.38 [a,b,c] (0.18 - 0.57)	0.51 [a,b,c,d,e,f] (0.43 - 0.58)	0.51 [a,b,c,d,e,f] (0.44 - 0.57)	0.51 [a,b,c,d,e,f] (0.42 - 0.61)
Average Angular Velocity (degrees per second)	81.1 (55.8 - 106.4)	71.3 (32.8 - 109.8)	75.3 (30.6 - 120.0)	69.0 (46.3 - 91.6)	67.3 (34.1 - 100.5)	60.1 (17.4 - 102.9)	22.6 [a,b,c,d,e,f] (0.9 - 44.2)	22.9 [a,b,c,d,e,f] (-13.8 - 59.6)	34.0 [a,b,c,d,e,f] (-24.5 - 92.6)

Data is given as mean (95% confidence intervals).

a = significantly different ($P < 0.05$) from drop jump set 1
b = significantly different ($P < 0.05$) from drop jump set 2
c = significantly different ($P < 0.05$) from drop jump set 3
d = significantly different ($P < 0.05$) from rebound jump set 1
e = significantly different ($P < 0.05$) from rebound jump set 2
f = significantly different ($P < 0.05$) from rebound jump set 3

	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 [c] (44.9 - 58.4)	49.3 [c] (40.2 - 54.5)	52.2 [a,b,c] (42.6 - 57.6)	62.5 [a,b,c] (52.9 - 67.9)	56.3 [a,b,c] (46.7 - 62.0)	60.7 [a,b,c] (51.2 - 66.3)
First Ground Contact(degrees)	149.0 (144.1 - 153.9)	152.2 (146.5 - 157.8)	151.5 (144.2 - 158.9)	157.9 (153.0 - 162.8)	154.5 (147.6 - 161.3)	154.2 (144.0 - 164.3)	153.0 (146.8 - 159.1)	150.1 (140.4 - 159.8)	151.1 (140.6 - 161.7)
Greatest Jump Depth (degrees)	132.5 (124.6 - 140.4)	131.2 (121.2 - 141.2)	131.9 (122.2 - 141.6)	117.0 [a] (101.7 - 132.2)	119.9 [a,b,c] (102.4 - 137.4)	118.2 [a,b,c] (92.9 - 143.6)	87.0 [a,b,c,d,e,f] (77.2 - 96.7)	87.7 [a,b,c,d,e,f] (70.4 - 105.1)	87.4 [a,b,c,d,e,f] (65.1 - 109.7)
Toe Off (degrees)	168.5 (164.5 - 172.4)	167.0 (163.2 - 170.8)	166.9 (163.5 - 170.3)	162.6 [a,b,c] (157.7 - 167.6)	162.6 [a,b,c] (155.9 - 169.3)	162.3 [a,b,c] (154.2 - 170.5)	156.7 [a,b,c,d,e,f] (152.9 - 160.4)	156.8 [a,b,c,d,e,f] (151.1 - 162.4)	157.8 [a,b,c,d,e,f] (150.8 - 164.8)
Flexion Range (degrees)	18.3 (11.7 - 24.8)	22.8 (9.5 - 36.1)	21.5 (11.1 - 31.8)	39.8 [a,c] (26.6 - 53.0)	33.4 [a,b,c] (16.7 - 50.1)	37.1 [a,c] (10.8 - 63.5)	66.0 [a,b,c,d,e,f] (55.2 - 76.9)	60.8 [a,b,c,d,e,f] (43.8 - 78.1)	62.5 [a,b,c,d,e,f] (37.8 - 87.1)
Extension Range (degrees)	36.2 (29.3 - 43.2)	35.7 (24.5 - 46.8)	36.9 (28.3 - 45.4)	45.7 (34.2 - 57.2)	43.3 [b,c] (30.6 - 56.0)	47.5 [b,c] (25.9 - 69.1)	70.7 [a,b,c,d,e,f] (61.6 - 79.8)	69.0 [a,b,c,d,e,f] (54.7 - 83.4)	69.1 [a,b,c,d,e,f] (49.0 - 89.2)
Flexion Time (seconds)	0.14 (0.11 - 0.17)	0.13 (0.10 - 0.16)	0.13 (0.10 - 0.16)	0.21 (0.14 - 0.28)	0.19 (0.13 - 0.25)	0.25 (0.13 - 0.37)	1.41 [a,b,c,d,e,f] (1.01 - 1.81)	1.31 [a,b,c,d,e,f] (0.84 - 1.78)	1.42 [a,b,c,d,e,f] (0.46 - 2.38)
Extension Time (Seconds)	0.15 (0.13 - 0.17)	0.35 (-0.06 - 0.77)	0.15 (0.12 - 0.18)	0.38 [a,c] (0.28 - 0.49)	0.35 [a,c] (0.23 - 0.47)	0.37 [a,c] (0.18 - 0.57)	0.56 [a,c,d,e,f] (0.46 - 0.65)	0.57 [a,c,d,e,f] (0.44 - 0.69)	0.58 [a,c,d,e,f] (0.41 - 0.75)
Average Angular Velocity (degrees per second)	77.4 (53.7 - 101.0)	57.4 (32.2 - 82.4)	56.6 32.6 - 80.6)	22.5 [a,b,c] (7.69 - 37.3)	35.2 [a,b,c,d] (13.3 - 57.1)	46.6 [a,b,c] (-9.7 - 103.0)	3.8 [a,b,c,d,e,f] (0.1 - 7.5)	0.7 [a,b,c,d,e,f] (-5.1 - 6.4)	9.9 [a,b,c,e] (-17.8 - 37.5)

Table 3: Exercise set results of the hip joint.

Data is given as mean (95% confidence intervals).

a = significantly different ($P < 0.05$) from drop jump set 1
b = significantly different ($P < 0.05$) from drop jump set 2
c = significantly different ($P < 0.05$) from drop jump set 3
d = significantly different ($P < 0.05$) from rebound jump set 1
e = significantly different ($P < 0.05$) from rebound jump set 2
f = significantly different ($P < 0.05$) from rebound jump set 3

	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 ^{c} (44.9 - 58.4)	49.3 ^{c} (40.2 - 54.5)	52.2 ^{a,b,c} (42.6 - 57.6)	62.5 ^{a,b,c} (52.9 - 67.9)	56.3 ^{a,b,c} (46.7 - 62.0)	60.7 ^{a,b,c} (51.2 - 66.3)
First Ground Contact(degrees)	113.9 (110.8 - 117.0)	113.4 (109.0 - 117.8)	113.4 (106.2 - 120.6)	109.4 (105.0 - 113.8)	110.2 (104.4 - 116.0)	109.4 (118.2 - 100.6)	89.1 (87.4 - 90.7)	88.0 (80.9 - 95.1)	88.9 (85.8 - 92.1)
Greatest Jump Depth (degrees)	72.6 (70.7 - 74.4)	72.5 (69.3 - 75.8)	72.1 (67.2 - 77.0)	69.6 (66.6 - 72.7)	69.5 ^{a,b,c} (64.8 - 74.3)	69.1 (64.0 - 74.1)	69.5 ^{a,b,c,d,e,f} (67.0 - 72.1)	72.9 ^{a,b,c,d,e,f} (61.6 - 84.2)	70.1 ^{a,b,c,d,e,f} (64.3 - 75.8)
Toe Off (degrees)	112.0 (109.7 - 114.3)	111.2 (197.8 - 114.6)	111.1 (107.2 - 114.9)	110.8 (108.9 - 112.7)	111.2 (108.5 - 113.9)	112.3 (107.1 - 117.5)	112.8 ^{d} (110.3 - 115.2)	111.0 (101.2 - 120.8)	114.4 ^{c,d,e,f} (108.8 - 120.0)
Flexion Range (degrees)	41.4 (38.4 - 44.3)	40.9 (36.4- 45.3)	41.6 (35.2 - 47.9)	39.8 (35.9 - 43.6)	41.9 (35.9 - 43.6)	40.2 (31.9 - 48.5)	57.2 ^{a,b,c,d,e,f} (50.6 - 63.8)	49.9 ^{b,d,e,f} (38.7 - 61.1)	53.0 ^{a,b,c,d,e,f} (42.7 - 63.2)
Extension Range (degrees)	39.4 (37.3 - 41.4)	39.5 (34.7 - 44.3)	39.0 (34.4 - 43.5)	41.4 ^{c} (38.7 - 44.0)	40.0 (35.1 - 44.9)	41.7 ^{c} (38.6 - 44.8)	41.7 ^{a,c} (39.1 - 44.3)	42.6 ^{a,c} (39.2 - 46.0)	43.0 ^{a,c} (38.6 - 47.3)
Flexion Time (seconds)	0.14 (0.11 - 0.17)	0.12 (-0.61 - 0.48)	0.13 (0.08 - 0.19)	0.20 (0.13 - 0.27)	0.17 (0.11 - 0.24)	0.20 (0.06 - 0.33)	1.11 ^{a,b,c,d,e,f} (0.68 - 1.53)	1.03 ^{a,b,c,d,e,f} (0.44 - 1.61)	0.76 ^{a,b,c,d,e,f} (0.10 - 1.42)
Extension Time (Seconds)	0.15 (-0.75 - 0.45)	0.35 (-0.26 - 0.96)	0.15 (0.10 - 0.21)	0.33 ^{c} (0.29 - 0.37)	0.34 ^{c} (0.27 - 0.37)	0.32 ^{c} (0.21 - 0.43)	0.32 ^{b,c} (0.25 - 0.38)	0.29 ^{b,c} (0.12 - 0.47)	0.31 ^{b,c} (0.11 - 0.52)
Average Angular Velocity (degrees per second)	21.0 (10.2 - 31.7)	24.4 (9.1 - 39.7)	33.3 (-3.6 - 70.1)	26.6 (16.2 - 37.1)	25.6 (10.6 - 40.6)	26.0 (4.1 - 47.6)	22.3 (14.5 - 30.1)	19.6 (31.4 - 7.8)	23.9 (6.4 - 41.5)

Table 4: Exercise set results of the ankle joint.

Data is given as mean (95% confidence intervals).

a = significantly different (P < 0.05) from drop jump set 1
b = significantly different (P < 0.05) from drop jump set 2
c = significantly different (P < 0.05) from drop jump set 3
d = significantly different (P < 0.05) from rebound jump set 1
e = significantly different (P < 0.05) from rebound jump set 2
f = significantly different (P < 0.05) from rebound jump set 3

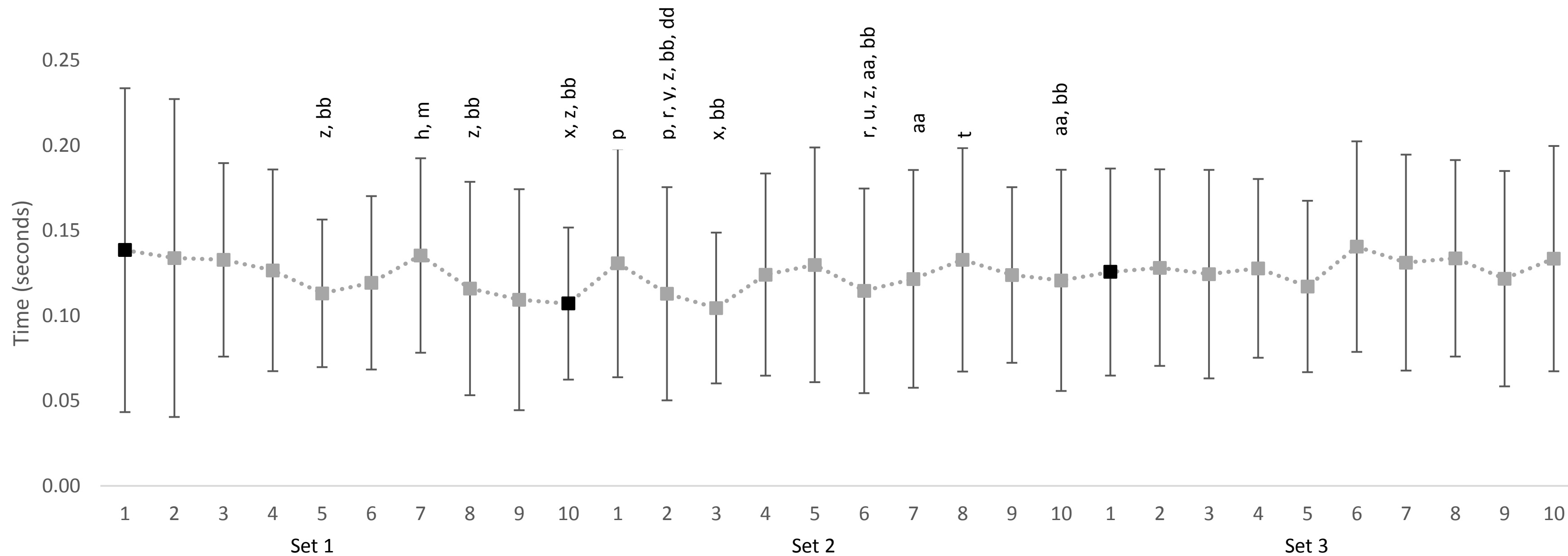

Figure 1: Drop jump exercise repetition knee flexion time result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at *P* < 0.05.

h = significant different to set 1 repetition 8, m = significant different to set 2 repetition 3, p = significant different to set 2 repetition 6, r = significant different to set 2 repetition 8, t = significant different to set 2 repetition 10, u = significant different to set 3 repetition 1, x = significant different to set 3 repetition 4, y = significant different to set 3 repetition 5, z = significant different to set 3 repetition 6, bb = significant different to set 3 repetition 8, dd = significant different to set 3 repetition 10

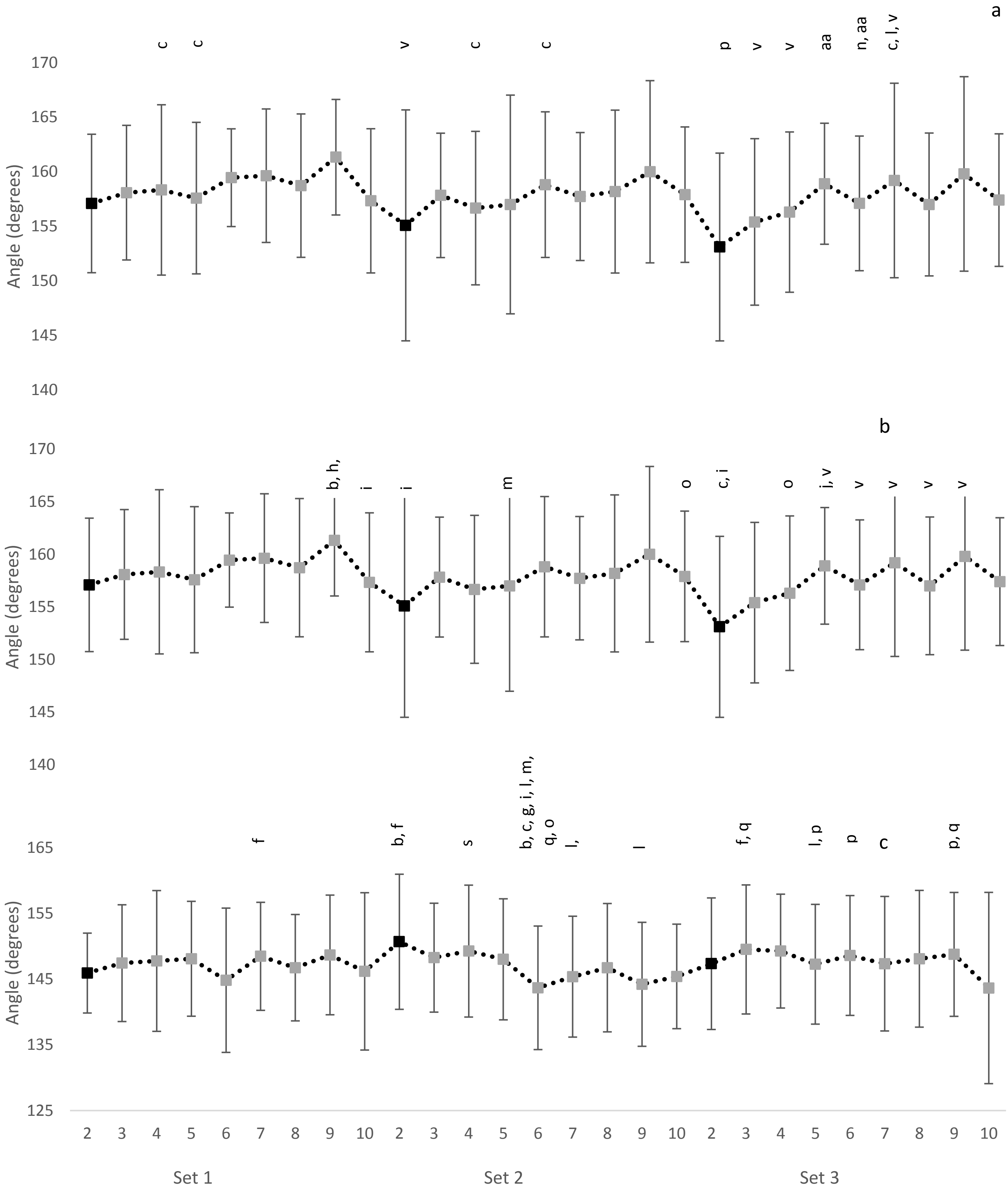
a
Angle (degrees)
170
165
160
155
150
145
140
b
Angle (degrees)
170
165
160
155
150
145
140
Angle (degrees)
165
155
145
135
125
2 3 4 5 6 7 8 9 10 2 3 4 5 6 7 8 9 10 2 3 4 5 6 7 8 9 10
Set 1
Set 2
Set 3

Figure 2a. Rebound jump exercise repetition knee joint flexion time result. 2b. Rebound jump exercise repetition knee joint angle at take-off result. 2c. Rebound jump exercise repetition knee joint angle at touch down result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at *P* < 0.05.
a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c = significant different to set 1 repetition 6, d = significant different to set 1 repetition 7, e = significant different to set 1 repetition 8, f = significant different to set 1 repetition 9, g = significant different to set 1 repetition 10, h = significant different to set 2 repetition 2, i = significant different to set 2 repetition 3, j = significant different to set 2 repetition 4, k = significant different to set 2 repetition 5, l = significant different to set 2 repetition 6, m = significant different to set 2 repetition 7, n = significant different to set 2 repetition 9, o = significant different to set 3 repetition 2, p = significant different to set 3 repetition 7.

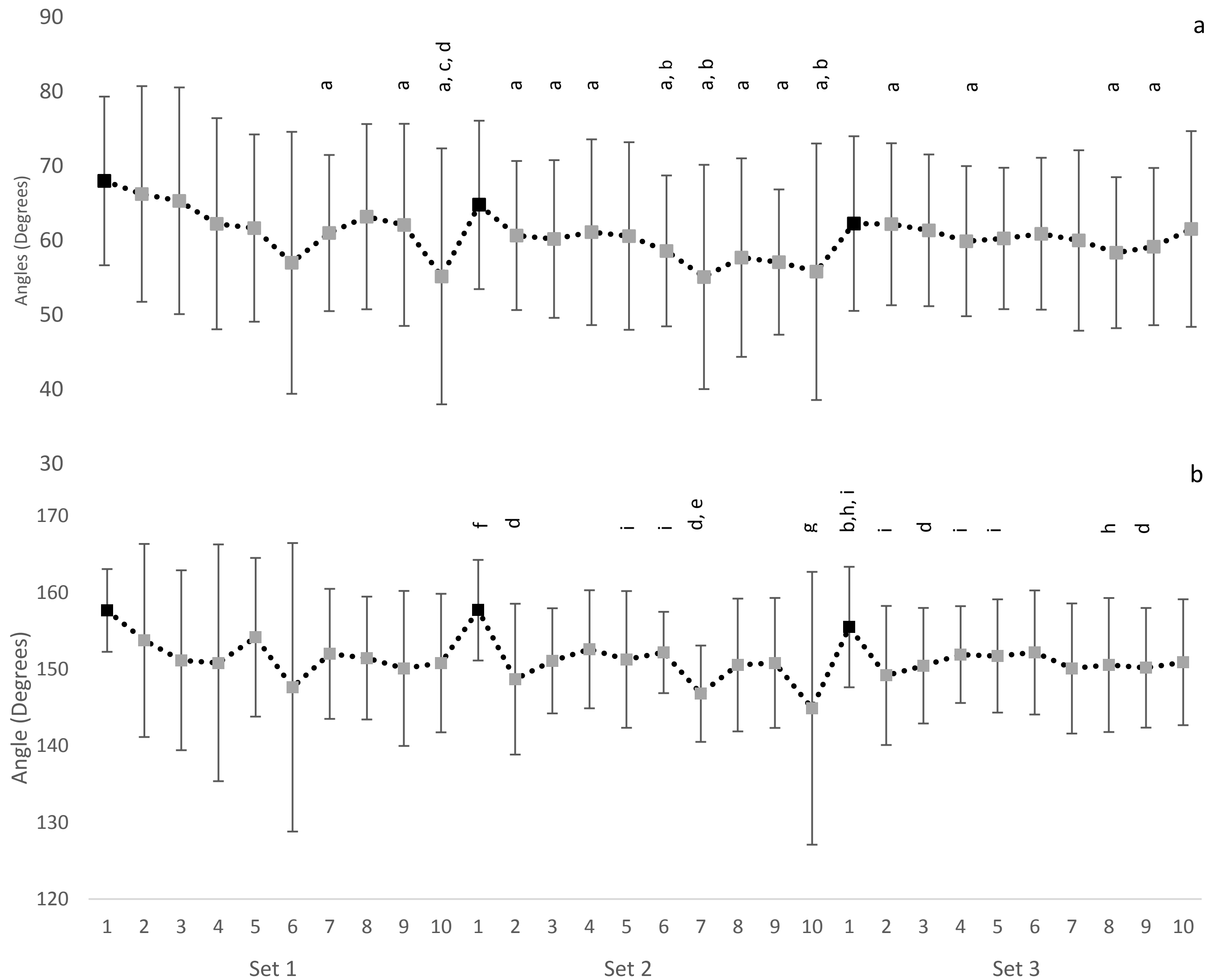

Figure 3a. Squat jump exercise repetition knee joint extension range result. 3b. squat jump exercise repetition knee joint angle at touch down result. Error bars represent SD. Black marker denotes first repetition of each set. Significance set at *P* < 0.05.
a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c = significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e = significant different to set 1 repetition 8, f = significant different to set 1 repetition 9, g = significant different to set 1 repetition 10, h = significant different to set 2 repetition 4, i = significant different to set 2 repetition 7.

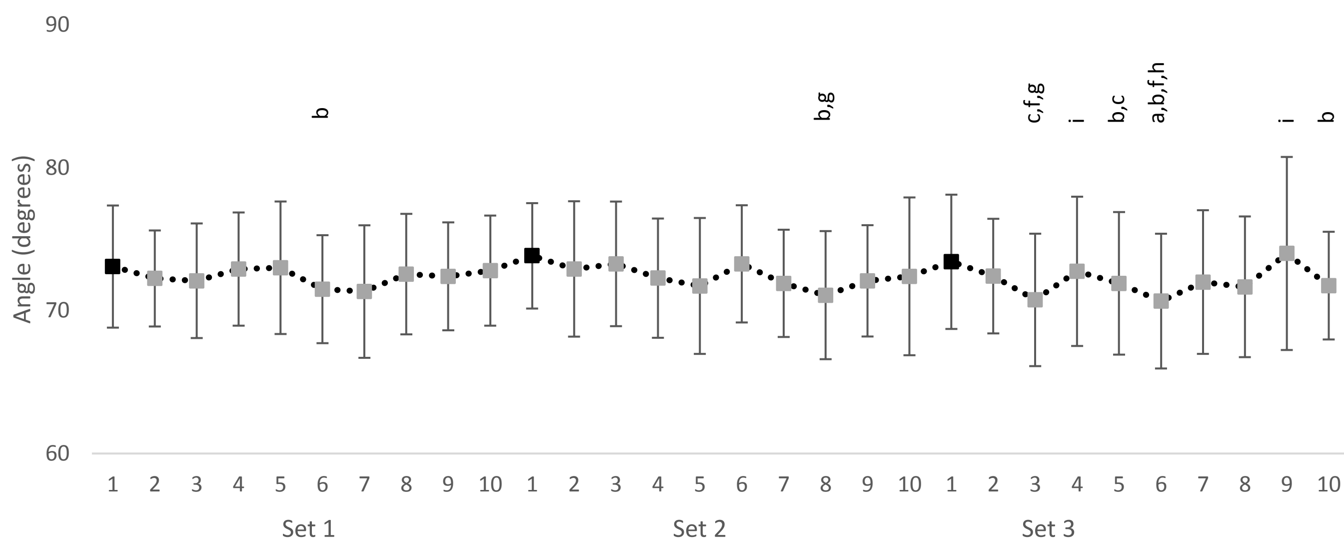

Figure 4: Drop jump exercise repetition ankle joint angle at peak joint flexion result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at *P* < 0.05.

a = significant different to set 1 repetition 3, b = significant different to set 1 repetition 4, c = significant different to set 1 repetition 5, d = significant different to set 1 repetition 8, e = significant different to set 2 repetition 2, f = significant different to set 2 repetition 3, g = significant different to set 2 repetition 4, h = significant different to set 2 repetition 6, i = significant different to set 2 repetition 8.

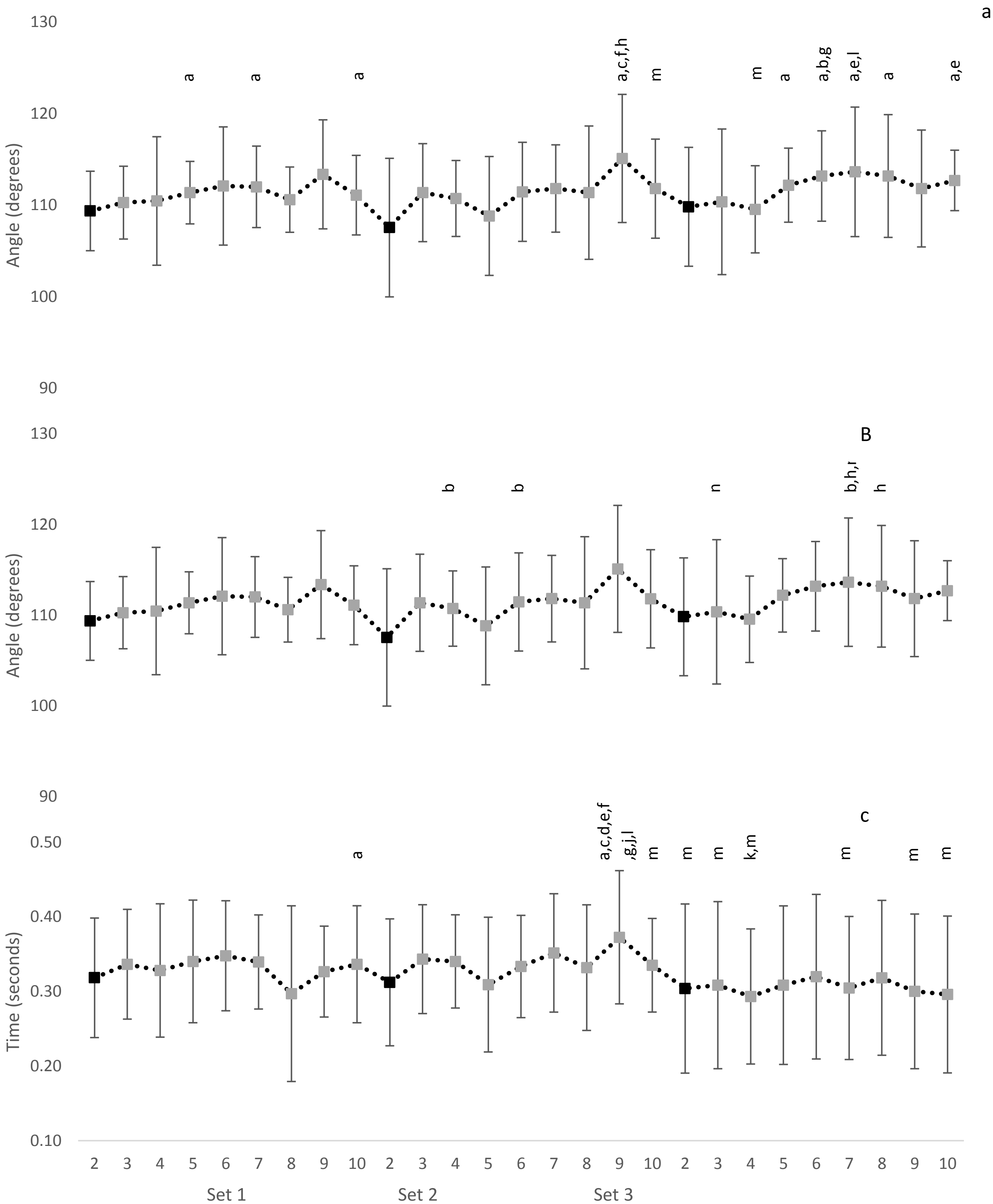
a
Angle (degrees)
130
120
110
100
90
a
a
a
a,c,f,h
m
m
a
a,b,g
a,e,l
a
a,e
B
Angle (degrees)
130
120
110
100
90
b
b
n
b,h,r
h
c
Time (seconds)
0.50
0.40
0.30
0.20
0.10
a
a,c,d,e,f
,g,j,l
m
m
m
k,m
m
m
m
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
10
Set 1
Set 2
Set 3

Figure 5a. Rebound jump exercise repetition ankle joint angle at take-off result. 5b. Rebound jump exercise repetition ankle joint flexion time result. 5c. Rebound jump exercise repetition ankle joint extension time result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at *P* < 0.05.

a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c = significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e = significant different to set 1 repetition 8, f = significant different to set 2 repetition 2, g = significant different to set 2 repetition 3, h = significant different to set 2 repetition 4, i = significant different to set 2 repetition 5, k = significant different to set 2 repetition 7, l = significant different to set 2 repetition 8, m = significant different to set 2 repetition 9, n = significant different to set 3 repetition 2, o = significant different to set 3 repetition 5, p = significant different to set 2 repetition 6.

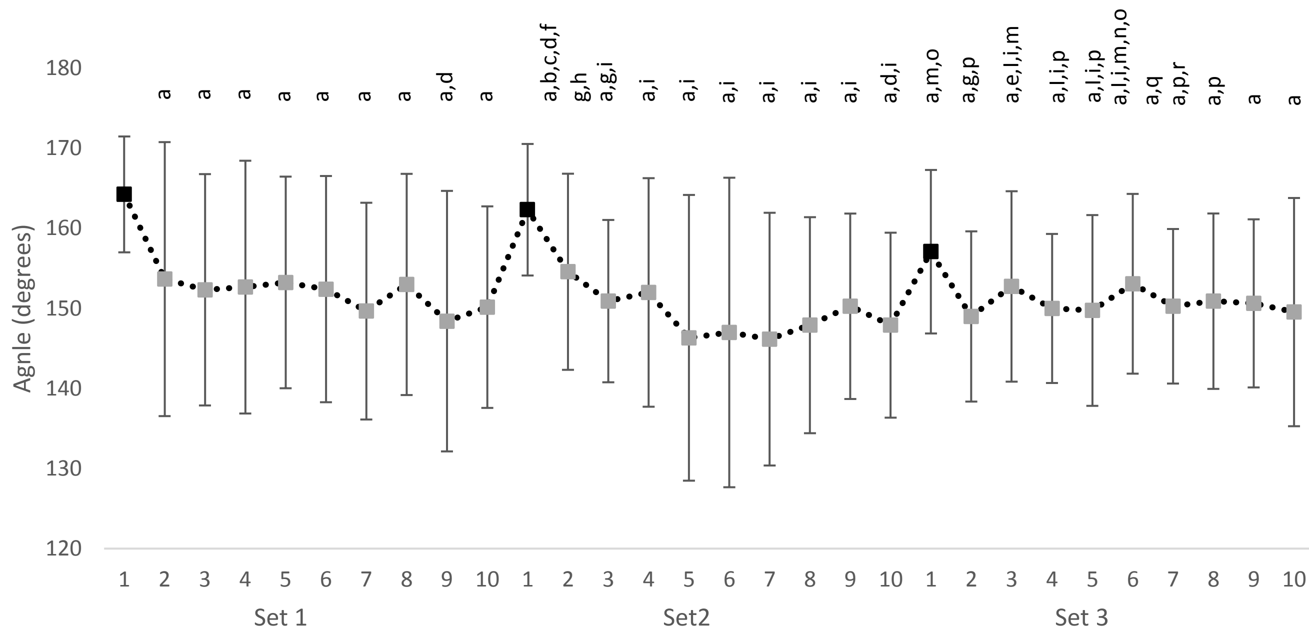

Figure 6: Squat jump exercise repetition hip joint angle at toe land result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at *P* < 0.05. a = significant different to set 1 repetition 1, b = significant different to set 1 repetition 3, c = significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e = significant different to set 1 repetition 7, f = significant different to set 1 repetition 8, g = significant different to set 1 repetition 9, h = significant different to set 1 repetition 10, i = significant different to set 2 repetition 1, k = significant different to set 2 repetition 4, l = significant different to set 2 repetition 5, m = significant different to set 2 repetition 7, n = significant different to set 2 repetition 8, o = significant different to set 2 repetition 10, p = significant different to set 3 repetition 1, q = significant different to set 3 repetition 4, r = significant different to set 3 repetition 6